

STUDIES OF HIGH ENERGY
LEPTON-NUCLEON SCATTERING

GUNNAR INGELMAN



Department of Theoretical Physics
University of Lund
Lund, Sweden

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Studies of High Energy

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by

Gunnar Ingelman

Department of Theoretical Physics
University of Lund

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Title and subtitle Studies of high energy lepton-nucleon scattering.	
Abstract The first part of this thesis is related to the problem of detecting charmed particles. A new technique for <u>observing very short decay paths in nuclear emulsions</u> is developed and applied on a sample of neutrino induced reactions. Techniques for producing thick pellicles of nuclear track emulsion are also developed. In the second part, <u>phenomenological investigations of deep inelastic lepton-nucleon scattering</u> are made. Monte Carlo computer programs, based on the parton model and perturbative QCD for the initial hard process and the Lund model for the following soft hadronization, are used to simulate these reactions and thereby obtain explicit results. Generally good agreement is found when comparing these with experimental data, thus supporting this basic framework. Predictions to test QCD are made. <u>Transverse momentum properties</u> are studied in detail, in particular effects from <u>soft gluon emission</u>. The properties of a <u>model for baryon production</u>, both from the target remnant and the colour force field, are discussed and the results found to agree with data. We show that, at the presently available energies, the observable energy flow is not due to QCD, but arises from the baryon production in the target fragmentation. In a model to explain the observed <u>Λ polarization</u>, we suggest a connection between the confinement of quarks and these polarization phenomena.	
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Signature Gunnar Ingelman

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This thesis is based on the papers listed below. It contains both theoretical and experimental work in the area of elementary particle physics with main emphasis on high energy lepton-nucleon scattering.

- I Detection of Short-Lived Particles in Nuclear Emulsions.
Nuclear Instruments and Methods 165 (1979) 1
(together with B. Andersson, G. Claesson, K. Söderström, I. Otterlund)
- II A Search for Very Short-Lived Particles Produced by Neutrinos in Nuclear Emulsion.
Lund preprint LUIP 8203.
(together with G. Claesson and K. Söderström)
- III On the Production of Thick Pellicles of Kodak NTB-3 Nuclear Track Emulsion.
Nuclear Instruments and Methods 180 (1981) 441
(together with G. Claesson and K. Söderström)
- IV On High Energy Leptonproduction.
Zeitschrift für Physik C9 (1981) 233
(together with B. Andersson, G. Gustafson, T. Sjöstrand)
- V Baryon Production in Lepton-Nucleon Scattering and Diquark Fragmentation.
Lund preprint LU TP 81-6,
to be published in Zeitschrift für Physik C.
(together with B. Andersson, G. Gustafson, T. Sjöstrand)
- VI Transverse Momentum Effects and Angular Energy Flow in Leptonproduction.
Lund preprint LU TP 81-8
(together with B. Andersson, G. Gustafson, T. Sjöstrand)
- VII A Semiclassical Model for the Polarization of Inclusively Produced A^0 Particles at High Energies.
Physics Letters 85B (1979) 417
(together with B. Andersson and G. Gustafson)



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...but the basic stuff
Is indestructible, so things remain
Intact, unharmed, until a force is found
Proportionate to their texture, to effect
Revision to their elements,...

Lucretius, De Rerum Natura (55 B.C.)

1. Introduction.

High energy physics deals with the basic constituents of matter and the interactions between them. From a philosophical point of view this problem has aroused man's interest since ancient times. The natural and appealing thought that all matter is built up of basic constituents, that can not be further divided, was first formulated by greek natural philosophers in the 5:th and 4:th century B.C.

It has, however, turned out that objects which seemed indivisible could in fact be divided when enough energy became available to overcome the attractive forces between the smaller constituents of the object. In this way it was found that the atoms were built up by a nucleus surrounded by electrons which are bound to the nucleus with an energy of the order electron volt (eV). The nucleus, in turn, is built up of protons and neutrons with binding energies of the order MeV (10^6 eV).

The general method to search for a possible internal structure of an object is to scatter some projectile particle against it. From the scattering of α -particles (helium nuclei) against a thin gold foil Rutherford could, in 1911, deduce the structure of the atom.

The smaller structures to be studied, the larger resolving power is needed. According to quantum mechanics a particle with momentum p can be described as a wave motion with wave length $\lambda = h/p$, where h is a fundamental constant. Hence, with a larger energy and a correspondingly smaller wave length the ability to probe small structures increases.

In the fifties beams of electrons having energies around 100 MeV, were used to study the structure of the atomic nucleus. With the construction of even more powerful particle accelerators it was possible to accelerate electrons to an energy of several GeV (10^9 eV). By scattering these electrons against protons it was found, in the late sixties, that also the proton has an internal structure. This structure is attributed to more fundamental objects, called quarks, that build up the proton and all other hadrons (i.e. strongly interacting particles). These quarks had been introduced as a consequence of a theoretical attempt to make a classification of the large number of experimentally observed particles, i.e. to find the periodic table of the elementary particles.

Today we can use not only beams of electrons but also muons and neutrinos having energies up to a few hundred GeV. All these particles are so-called leptons, a family of fundamental particles characterized by not participating in strong interactions and to the best of our knowledge being pointlike, i.e. structureless down to $\sim 10^{-18}$ m.

When the beam energy is increased the leptons do not interact with the target nucleon (proton or neutron) as a whole but rather with its constituent quarks. In such "deep inelastic" collisions, a large energy and momentum is transferred from the lepton to the quark which is thus "kicked out" of the nucleon.

Experimental and theoretical efforts in this area of particle physics have given us much information about the internal structure of the nucleon and the basic forces acting between quarks and leptons, which today are regarded as the fundamental building blocks in nature.

Phenomenological studies, i.e. an interplay between theoretical ideas and experimental results, of high energy lepton-nucleon scattering is also the main subject of this thesis. The first three papers are related to an experimental search for short-lived particles, in particular charmed particles which contain a new, heavy quark. In the following three papers the lepton-nucleon reaction mechanism is studied in more detail with respect to the strong force acting between the quarks. One

essential assumption made in this study is utilized, in the last paper, to give a possible explanation of some observed spin polarization phenomena.

2. The E553 experiment.

This experiment was performed at Fermilab in USA by an international collaboration with participants from Cornell, Lund, Oklahoma, Pittsburgh, Sydney and Toronto. The aim was to search for new, short-lived particles produced by neutrinos in a nuclear emulsion target.

The discovery of the ϕ particle in 1974, which was awarded the 1976 Nobel price, made a very strong support for the hypothesis that all hadrons are built up by quarks. The new thing was, however, that besides the original, light quarks (called up, down and strange) this discovery implied the existence of a new, heavy quark carrying a new quantum number labelled "charm". A whole new family of "charmed" particles containing this quark has since been discovered. It was estimated that single charmed particles could be produced at a relatively high rate (5-10%) in neutrino induced reactions. From the theory of weak interactions their lifetime was estimated to about 10^{-13} seconds corresponding to a decay path around 100 μm . The only detector capable of resolving such short tracks is nuclear emulsion, which also has the additional advantage to cover the whole 4π solid angle. This would enable a detailed study of both the production and decay of these

charmed particles.

The experimental set-up also included a magnetic spectrometer for momentum measurements and a calorimeter of a novel design using flashtube chambers. A report of the experiment was given at the Neutrino 79 conference [1].

The primary responsibility of the Lund group was to handle the emulsion target consisting of 15 liters of Kodak NTB-3 nuclear emulsion. Since this is not delivered in pellicle form by the manufacturer we had to pour the emulsion gel and make the pellicles ourselves. This nontrivial matter is the subject of paper III.

After exposing the emulsion to the neutrino beam it is processed and the resulting tracks from charged particles can be observed using a microscope. The high spatial resolution is ultimately limited by the size of the silver halide grains, $\sim 1 \mu\text{m}$. For practical reasons it is, however, difficult to visually detect particles which decay within about $10 \mu\text{m}$ from their production vertex. It is then clearly desirable to have an objective method to be able to determine whether there is a secondary vertex or not, and then find out which tracks originate from this second vertex. Such a method has been developed and is presented in paper I.

The principle is to make a χ^2 test of the hypothesis that all particles emerge from the same point in the emulsion. Production and decay vertices as close as $0.5 \mu\text{m}$ can then be resolved, corresponding to a lifetime of the order 10^{-15} seconds. No such very short-lived particles were found in the investigation presented in paper II. However, we found a track with a kink which is consistent with a charm decay to a single charged particle.

In Lund we also developed computer programs to simulate neutrino reactions in general and charm production and decay in particular. By using these programs we analysed acceptance problems of the apparatus. A general finding was that the magnet gap was too narrow so that a large fraction of the produced particles would be lost in the magnet iron yokes. Unfortunately, these studies were initiated too late to have a real influence on the design of the apparatus for the first run which took place in early 1979. For the planning of a second run we made extensive studies in order to improve the apparatus. Some of these investigations are described in a set of internal reports [2]. For various reasons, however, the second run was never realized and the physics results of the first run were very limited. Due to some problems with parts of the experimental equipment only 43 events were located in the emulsion. Of these 43 events, 4 were of further interest, but none could be identified well enough to give solid conclusions. With some more time, or manpower, for preparing the experiment and a bit of luck, E553 might have given important results in a very topical field.

3. Hard and soft processes in lepton-nucleon scattering.

Although there is by now a wealth of results in support of the quark hypothesis it is also an experimental fact that quarks have not been observed as free entities. This has led to a general belief among particle physicists that quarks never can appear as free objects but are always confined within the hadrons.

A quark that has been kicked out of a nucleon by a hard scattering process, like the large energy transfer in a lepton-nucleon collision, will then in some way give rise to the experimentally observed shower of hadrons. This "hadronization" process is basically of a soft nature, i.e. involving only small momentum transfers, and occurs on a longer space-time scale than the initial hard scattering process. This transformation from a kicked out quark to a shower, or jet, of hadrons has in a joint effort been studied by several members of the Lund theory group and resulted in the so-called Lund model for soft hadronization.

Here, it is visualized that a strong force field is stretched from the kicked out quark to the target remnant quarks. This field is essentially of a one-dimensional character and has a constant energy per unit length of about 1 GeV/fm. It is then possible to lower the potential energy by producing, out of the field energy, quark-

antiquark pairs which are pulled apart by the field. These quarks can combine to form the observed mesons. This break-up of the force field by the production of $q\bar{q}$ pairs is basically of a stochastic nature leading to an iterative process. It can therefore be implemented in terms of a Monte Carlo computer program [3] that simulates this transition, called fragmentation, from quarks to particle showers. In principle it is possible to calculate everything analytically by hand using this model, but if more complicated properties are to be studied this becomes very unpractical. One advantage with having a computer program for this purpose is that complete events are simulated. This makes it possible to study, not only single particle properties, but also correlations among particles and even the structure of the whole event.

In the candidate theory for the strong interaction, Quantum Chromo Dynamics or QCD for short, the strong force between quarks is described as an exchange of massless quanta called gluons. The strong interaction "charge" is a quantum number, given the name colour, which is carried by both quarks and gluons. This theory is analogous to the quantized version of electrodynamics but mathematically more complicated. Hence, it can only be solved approximately by using perturbation theory for interactions involving large energy transfers. For soft processes, which have relevance for the confinement of quarks, models like the one described above have to be used.

In the Lund model the generalization of the one-dimensional constant force field to three dimensions is made in a relativistically covariant way by using the dynamics of the massless relativistic string. This string is stretched from the kicked out quark to the target remnant. It is also possible to have a localized excitation on the string, a kink, which carries energy and momentum and can be taken as a representation of the gluon.

A basic assumption is that the lepton-nucleon reaction mechanism involves two space-time scales. Through the weak or electromagnetic interaction a large energy and momentum is transferred from the lepton to a quark via the exchange of a W-boson or a photon. In this initial, short phase the struck quark can also emit a gluon with sizable energy as can be calculated using perturbative QCD. The following long scale corresponds to the soft hadronization where the coloured partons, quarks and gluons, are connected by the strong "colour" force field which then breaks up to produce the final state of observable particles.

A Monte Carlo program, tailored to simulate lepton-nucleon interactions, has been developed [4]. This program, which uses the general routines [3] for the hadronization process, has been used to obtain many of the results presented in paper IV to VI.

Our model for lepton-nucleon interactions is described in some detail in paper IV where also the main features of the resulting event structures are studied. The ordinary type of event is that the kicked out quark gives one jet of particles moving forward in the laboratory system. To a first approximation in QCD two new configurations can appear. These give rise to 2-jet events, having two jets of particles that are separated in space. One case is the gluon emission mentioned above and in the other case the lepton interacts with a gluon, in the target, resulting in an ejected quark-antiquark pair. The paper investigates some observables which are sensitive to the occurrence of these event configurations, in particular the transverse momentum components, p_t , of the produced particles. Generally good agreement is found when comparing the results with experimental data from the European Muon Collaboration (EMC) at CERN. This supports both the QCD theory of quarks and gluons and also our model for jet fragmentation. To check the correctness of the QCD description in more detail, the paper suggests specific tests and makes definite predictions using a single particle p_t -trigger condition to get an enriched sample of 2-jet events. Such tests, which were later carried out by the EMC group, has further strengthened our confidence in this basic framework.

When viewing the reaction in the center of mass system there will be a quark jet going forward and also one jet of particles moving backwards, caused by the left-over quarks in the target nucleon. In paper V the hadronization

of this target remnant is studied in more detail. Usually, when one of the three valence quarks in the proton is hit by the lepton, this target remnant will be a diquark. The two quarks in this diquark stretch the colour force field, to the forward moving quark, in a stepwise manner. When the field breaks up there is then the possibility that these two quarks will enter different hadrons. Of course, there will always be one baryon (particle with three quarks) produced to carry the baryon number of the initial state nucleon. This study of the target fragmentation jet provides new information about the structure of the colour force field with relevance also to other types of particle collisions.

In a similar way as quark-antiquark pairs are produced in the break-up of the force field it may be possible to produce diquark-antidiquark pairs which will result in baryon-antibaryon pairs. The consequences of this new idea is explored in paper V and we find that the main characteristics of the protons and antiprotons observed in the EMC experiment are reproduced, thus supporting our baryon production model. The paper also discusses specific correlation properties that these baryon-antibaryon pairs are expected to show.

In paper IV it was found that in order to reproduce the experimental p_t -spectra one had to use fairly large values for the so-called primordial transverse momentum; in fact, unphysically large if it were to be interpreted simply as the expected Fermi motion of the quarks inside the target

nucleon. As is shown in paper VI, this problem can be resolved if effects from soft gluon emission are also taken into account. These are low energy gluons which do not give rise to separate jets of particles but still can have effects on the p_t of the hadrons and give a recoil to the leading quark. These p_t effects are rather similar to those from the primordial transverse momentum but, as is shown in the paper, it is possible to distinguish the two sources of transverse momentum.

It has been shown earlier that QCD predicts a characteristic forward-backward asymmetry in the angular energy flow at the parton level. Our study in paper VI shows that the hadronization process washes out this asymmetry. In fact, the dominating part of the observable asymmetry arises from the production of a baryon in the target jet. This shows the importance of not only calculating properties of quarks and gluons, in the initial phase, since effects arising in the following hadronization process often dominate and therefore have to be taken properly into account.

4. Spin polarization from quark confinement.

An important assumption in the Lund model is that the stretched-out colour force field is of a one-dimensional character and does not have any transverse motions. It has been possible to obtain support for this idea from a rather different kind of experimental results. It has been found that Λ particles which are produced (inclusively) in high energy proton-proton collisions have their spins polarized, even though the spins of the initial state protons are not polarized. Moreover, this polarization was found to increase with the transverse momentum of the Λ particle. This was actually quite a surprise since it had been generally believed that polarization phenomena should be unimportant at high energies.

In paper VII we suggest a possible mechanism to account for this phenomenon. The Λ particle is here regarded as a leading particle built up by a ud -diquark and a strange quark from an $s\bar{s}$ pair produced in the break-up of the colour force field, which is stretched by the diquark originating from the projectile proton. The $s\bar{s}$ pair becomes polarized in order to compensate for an orbital angular momentum arising from their transverse momentum. The fact that this model gives a resulting Λ polarization which is both of the correct direction and magnitude is a strong support for the absence of transverse excitations of the string-like force field. This is also the first paper to suggest a connection between the confinement of quarks and polarization phenomena.

5. The Monte Carlo method.

An essential tool to obtain the results presented in this thesis has been the specially developed Monte Carlo computer programs. These make use of a random number generator to obtain values of stochastic variables according to various specified frequency distributions. This makes it possible to simulate the reaction mechanism and thereby obtain complete events. The purpose is first of all to study the results of the physical models involved and facilitate a close comparison with the experimentally observed events. This kind of program can also be used to investigate the ability of some experimental detector arrangement to extract the wanted information.

The programs have also been used by experimental groups. The European Muon Collaboration at CERN has used it to make comparisons between predictions of the theoretical models, as implemented in the program, and their experimental results, and in general good agreement has been found. Also some groups studying neutrino interactions in the BEBC bubble chamber have started to use the program in a similar way.

In collaboration with Canadian physicists this program was also extended to simulate the type of events expected to occur in a high energy electron-proton collider as planned

in the Canadian CHEER project. Here it was planned to construct an accelerator giving 10 GeV electrons to be collided with 1000 GeV protons in the Fermilab accelerator. The resulting Monte Carlo program [5] was used to investigate the ability of the planned detector set-up to detect particles and reconstruct the kinematics of the events. Some specially interesting topics were also studied, e.g. the possibility to detect semileptonic decays of the expected top particles.

The general principle for developing this program was to extrapolate current theories and ideas to the much higher energy region that can be reached in the future with such an accelerator. By using the program one can get a clear picture of the kind of events we expect to occur. This will make it easier to recognize any deviations that indicate new physics. One must, of course, realize that completely new phenomena may occur in these extremely energetic collisions, or put in another form:

"There are more things in heaven and earth, Horatio,
than are dreamt of in your philosophy."

- Hamlet in "Hamlet", act I, scene V.

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